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Interim Report
April 1981

DIRECT WRITE ION LITHOGRAPHY

Hughes Research Laboratories

R. Vahrenkamp

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Air Force Systems Command
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An ion column utilizing mass-separated silicon ions at 150 kV (300 keV Si^{++}) is an optimum choice for direct-write ion lithography. Since liquid metal ion source technology requires the use of copper or gold alloys of silicon to produde silicon ions, a mass separator is incorporated into the focusing column to remove the undesired ion species from the beam. Exposed depth measurements in PMMA were made using unseparated flood and focused ion beams from LM sources. The

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range of silicon ions in resist at 200 keV is greater than 0.5 μm. The resist was less sensitive to the high current density (1 A/cm^2) focused beam than to the low current density (1 $\mu A/cm^2$) flood beam. Repolymerization of the resist occurred at a dose approximately 80-90% of that required for maximum range due to the heavy gold or copper ions. The problems of range loss, repolymerization, and stray dc magnetic fields are also reasons for using a mass-separated column.

Although more complex than a single accelerating lens, a high-resolution focusing column utilizing an ExB separator is feasible. Care will be taken in designing the separator to minimize astigmatism.

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I. INTRODUCTION

This is the second interim technical report in the Direct-Write Ion Lithography program. The overall objective of this program is to conduct a theoretical and experimental study directed toward utilizing liquid metal (LM) ion sources in an ion-beam accelerating and focusing column that is designed for performing direct-write ion-beam lithography. The program consists of four technical tasks:

(1) Optimal ion source for resist exposure

(2) Electrostatic scanning

(3) Alignment techniques

(4) Ion lithography column design.

Task 1 will determine the optimal ion source for direct-write ion lithography. The optimal ion species and energy for resist exposure will be investigated. Resist-exposure experiments will be performed with candidate LM ion sources and focused ion beams, as well as with ion-transmission masks and conventional ion sources. In parallel with the resist-exposure investigation, the technology of LM ion sources will be explored to determine which ion species can be produced. From these, the ion species that is optimal for resist exposure will be chosen. A LM source of the chosen ion species will be fabricated to demonstrate focused-ion-beam resist exposure. Sample exposures will be delivered to RADC/ESE.

Task 2 will investigate the maximum "distortion-free" electrostatic scan field. A theoretical analysis will be made to determine the dynamic correction signals that can be applied to the final-focusing lens and the deflector to minimize the deflection aberrations. The size of the scan field in our focusing column will be measured with and without application of the most significant (field curvature) dynamic correction.

Task 3 will investigate alignment techniques for direct-write ion lithography. Experiments will be performed to evaluate the use of secondary-electron detection and of photodetection for the location of alignment marks by the focused beam.

Task 4 will develop the design of an ion-focusing column and interface that can replace the E-beam column on the existing RADC/ESE E-beam mask fabrication system. A theoretical ion-optical design will be made of the column elements. Then mechanical designs of the column and interface will be developed and layout drawings prepared. The column and interface electronics will be specified in block-diagram form. A design review will be held, and, after approval has been obtained, the cost of constructing the focusing column and interface will be estimated.

II. SUMMARY

Work continued during the last quarter on Task 1, Optimum Ion Source for Resist Exposure. Using four different alloys as ion source material, exposed depth measurements for PMMA were made for both low- and high-current-density ion beams. The alloys used were Au-Si and Cu-Si for Si ions and Au-Be and Cu-Be for Be ions. For the low-current-density exposures, the cylinder lens apparatus described in the last quarterly report was used; for the high-current-density exposures, the single-lens focusing column was used. The difference in current density between the two systems is $\sim 10^6$. After exposure, the large-area patterns were developed for 60 sec in 2:3 MIBK, and the depth was measured with a surface profiler. The results can be summarized as follows:

- The heavy Au and Cu ions tend to re-polymerize positive resist at a dose that corresponds to approximately the maximum exposure range.
- The dose required for a high-current-density beam to expose a given resist thickness is greater than for a low-current-density beam.
- When using mass-separated Be and Si ions, the exposed depth at a given energy is greater than for nonseparated beams at maximum exposure.
- The PMMA is more sensitive to Si ions than to Be ions.

Based on the data to date, the major questions of Task I, can now be answered:

- A column voltage of 150 kV is sufficient to expose 0.5 µm of resist using Si ions and 1.0 µm of resist using Be ions.

- Mass-separated ion beams should be used to eliminate repolymerization and range degradation of positive resist. Mass separation also eliminates the contamination problems that might be caused by having gold or copper ions in the beam.

- Si ions should be used to expose resist on Si substrates if chemical contamination is to be avoided.

The major disadvantage of a mass-separated focusing column is its complexity and cost. The mass separator is also an additional source of beam aberration, and care must be taken to design the system properly. We are now in a position to make mass-separated focused beam exposures with Si ions. The tests are scheduled to begin during the next quarter, and should provide a substantial input to the design and expected performance of the RADC/ESE column.

III. TECHNICAL PROGRESS ON TASK I

The results from the now nearly complete Task I suggest the course of future activity for a direct-write ion-lithography system. These results are discussed in detail below.

A. Ion Species

Numerous ion species have been suggested throughout the program as possible candidates for resist exposure. The best choice now appears to be Si ions, and possibly Be ions as a second choice. Both silicon and beryllium must be alloyed with either gold or copper to obtain a material compatible with LM ion source technology. Table 1 lists the alloys used in the testing program. The Au-Si and the Cu-Si alloys (with high Si percentages of 18 at.% and 30 at.%, respectively) appear to be the best choices.

Table 1. Test Alloys

Alloy, at.%	Melting Point, °C
$Au_{60} - Be_{40}$	600
$Au_{72} - Si_{18}$	370
$Cu_{60} - Be_{40}$	900
$Cu_{70} - Si_{30}$	800

B. Resist Exposure

We considered from the outset of the program the possibility of using the unseparated ion beam to expose resist. If successful, such a technique would significantly reduce the cost and complexity of the column. Thus, each test to date has evaluated resist exposure using unseparated ion beams. This evaluation consisted primarily of:

- Preparing alloys of light elements compatible with LM ion source technology
- Obtaining depth measurements in exposed PMMA for unseparated beams at both low and high current densities
- Obtaining exposure-depth measurements for mass-separated beams at high and low current densities.

All of these tests have been completed except an evaluation of a high-current-density mass-separated beam. This test can now be done, since a focusing column with mass-separation is now available at HRL.

Low-current-density exposures were made on the apparatus shown schematically in Figure 1. The cylinder lens, which has a voltage ratio of 10, is used to collimate the ion beam to ~1 cm in diameter. The ion source for this apparatus is the same as that used for the focused-beam exposures in the single-lens column. Numerous exposures through the 0.5-mm aperture were made as a resist-coated wafer was stepped behind the aperture. High-current-density focused-beam exposures in the form of 150-μm x 150-μm rasters were made at varying doses. Since the maximum scan rate of 2 μsec/pt was limited by the speed of the computer/pattern-generator electronics, extremely low doses could not be obtained. In all cases, the PMMA was developed for 60 sec in 2:3 MIBK, and a DEKTAK surface profiler was used to measure the depth of exposed resist.

The results of the experiments to date are shown in Figures 2 and 3 and summarized below:

- The gold or copper usually caused the resist to polymerize at a dose of about 80 to 90% of that required for maximum range. The copper polymerization occurred at a slightly higher dose than for gold.
- To obtain maximum depth required a higher dose for the high-current-density exposures than for the low-current-density exposures.
- The resist is more sensitive (in terms of C/cm^2) to the heavier Si ions than to the Be ions.

Figure 4 shows the data replotted as a function of ion energy for an indication of maximum range. Earlier data from the mass-separated, low-current-density experiments are also included. There appears to be a loss of range when using the unseparated beam. This loss is somehow caused by the implanted copper or gold layers and may be due to a change in the resist properties as the repolymerization phenomenon begins to take place. At any rate, the column voltage would need to be significantly higher if an unseparated beam were used. It is normally assumed that singly and doubly changed ions with the same energy will interact with the resist in an equivalent manner. This assumption is probably

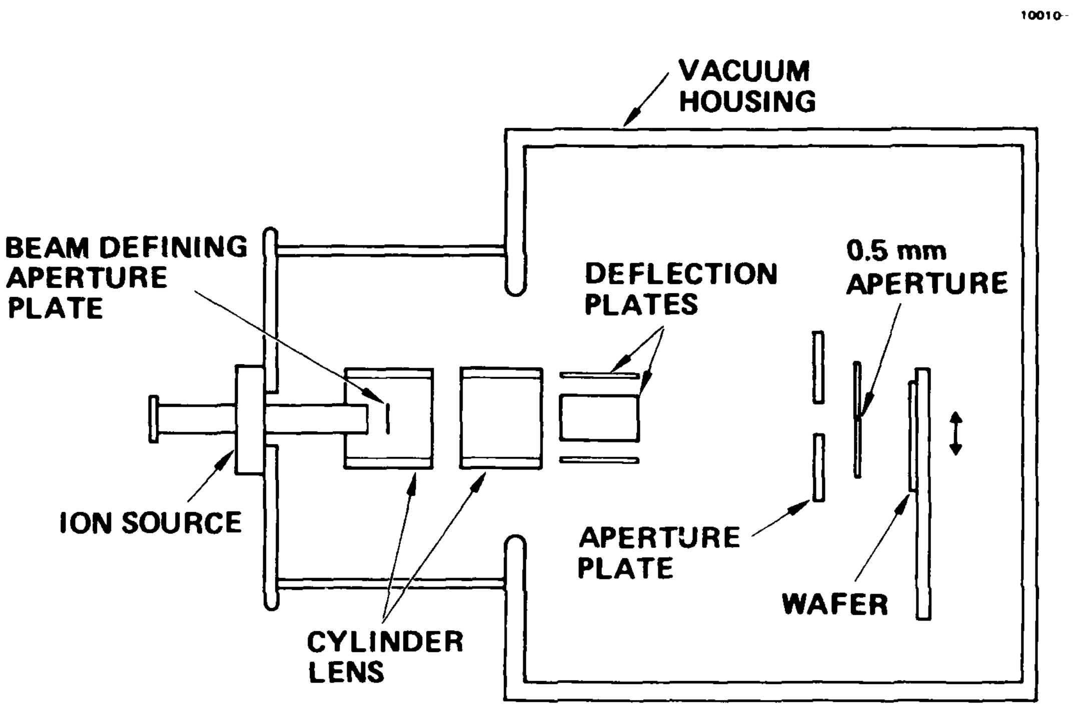

Figure 1. Schematic of the low-current-density exposure apparatus.

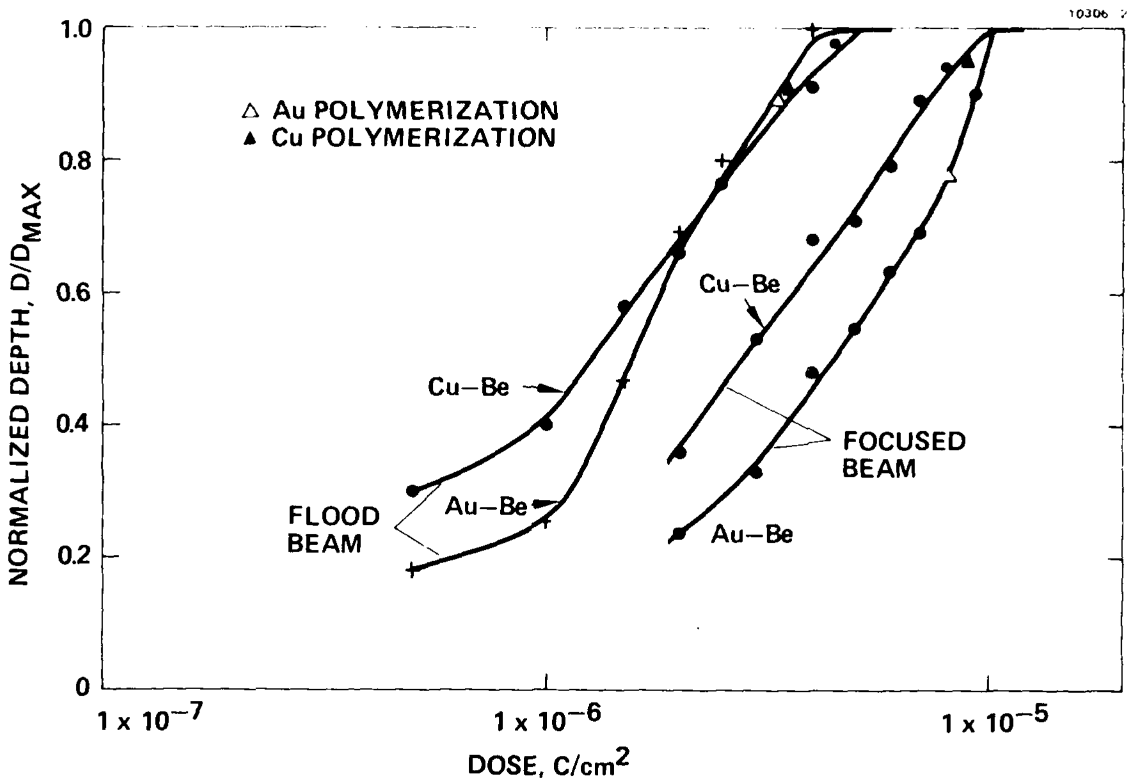

Figure 2. Exposure curves for the beryllium alloys.

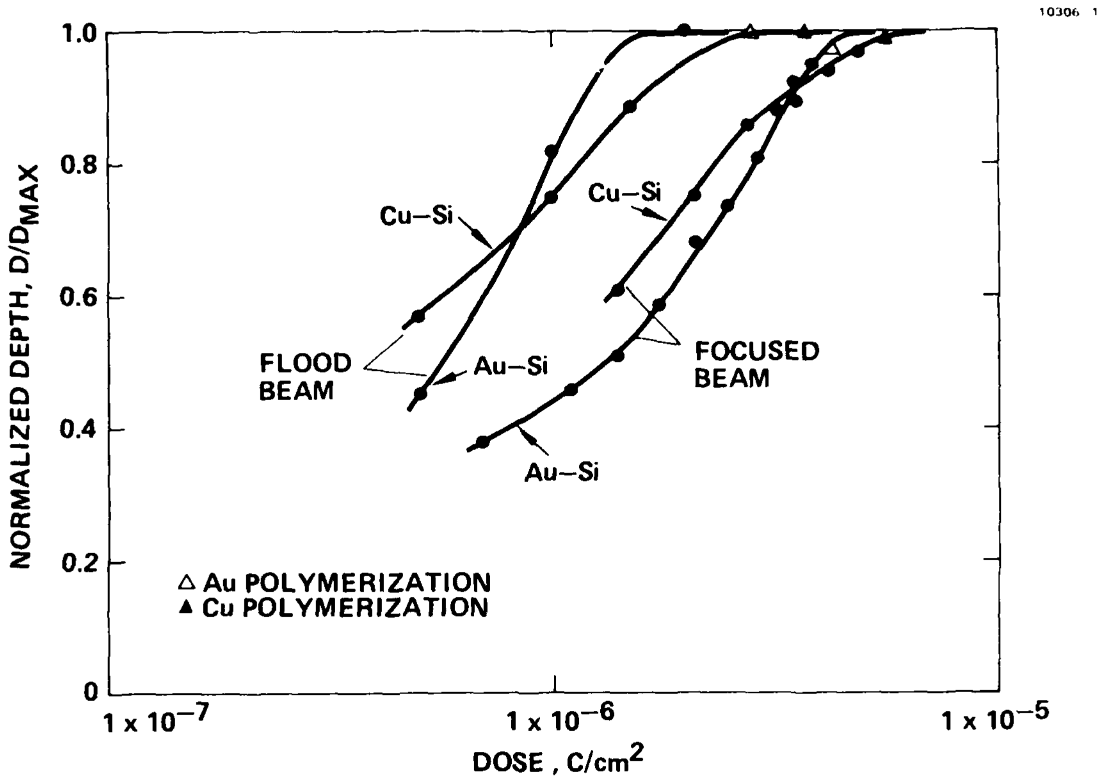

Figure 3. Exposure curves for the silicon alloys.

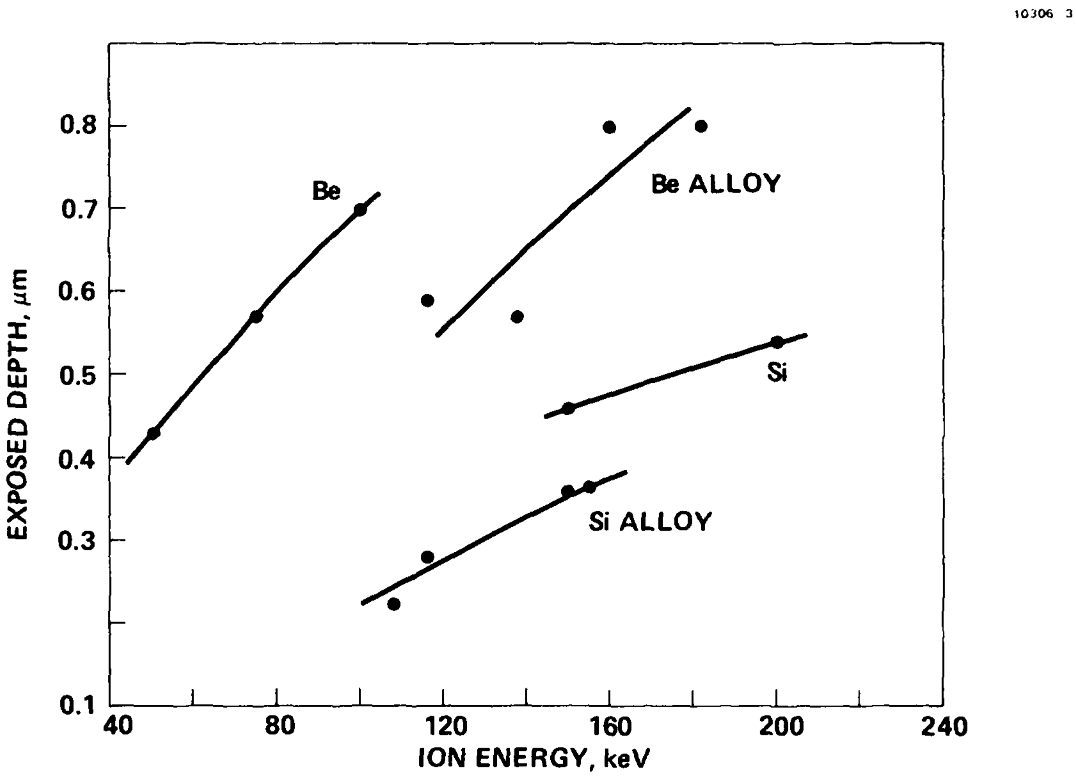

Figure 4. Depth comparisons for separated and unseparated beams.

not valid, and the mass separated ion exposures planned for next quarter will help answer this question.

Our experiments suggest several interesting questions concerning resist exposure by ion beams generated from LM ion sources. Current density effects, polymerization of positive resist, and range loss are all areas which would need to be further investigated if an unseparated beam appeared feasible. But it appears at this point that the tradeoff to a more complex mass-separating column is necessary. In this way, any problem concerning device contamination by either the gold or copper can be avoided, and the polymerization and range difficulties discussed above can be eliminated.

In addition to the raster scans, individual line scans were also exposed with the focused ion beam to evaluate spatial resolution. The lines shown in Figure 5 were obtained using the Cu-Be ion source. The earth's magnetic field caused the beam to mass-separate because the focusing column lacked magnetic shielding. The shallow profile was exposed by Cu^{+} ions, while the next two lines were exposed by Be^{+} and Be^{++} ions, respectively. The exposed linewidth for the Be^{++} line is ∿3300 Å. For a column utilizing a mass separator, the earth's small dc magnetic field should not present a serious problem, whereas an unseparated beam would require carefully designed magnetic shielding.

C. Implications of a Mass-Separating Focusing Column

One drawback to incorporating mass separation in a focusing column is the higher degree of complexity (cost) involved. The major differences in the two types of columns are shown schematically in Figure 6. Because of its "straight-through" capability, an ExB separator appears to be the most promising. In addition to the separator, another lens must be used to provide a crossover which is then demagnified by the final lens. Pre-lens deflection may be necessary to achieve very high resolution.

Because the LM ion source typically operates with an energy spread in the range of 5 to 15 eV, a fairly high degree of astigmatism can be introduced into the beam if care is not taken in the design of the

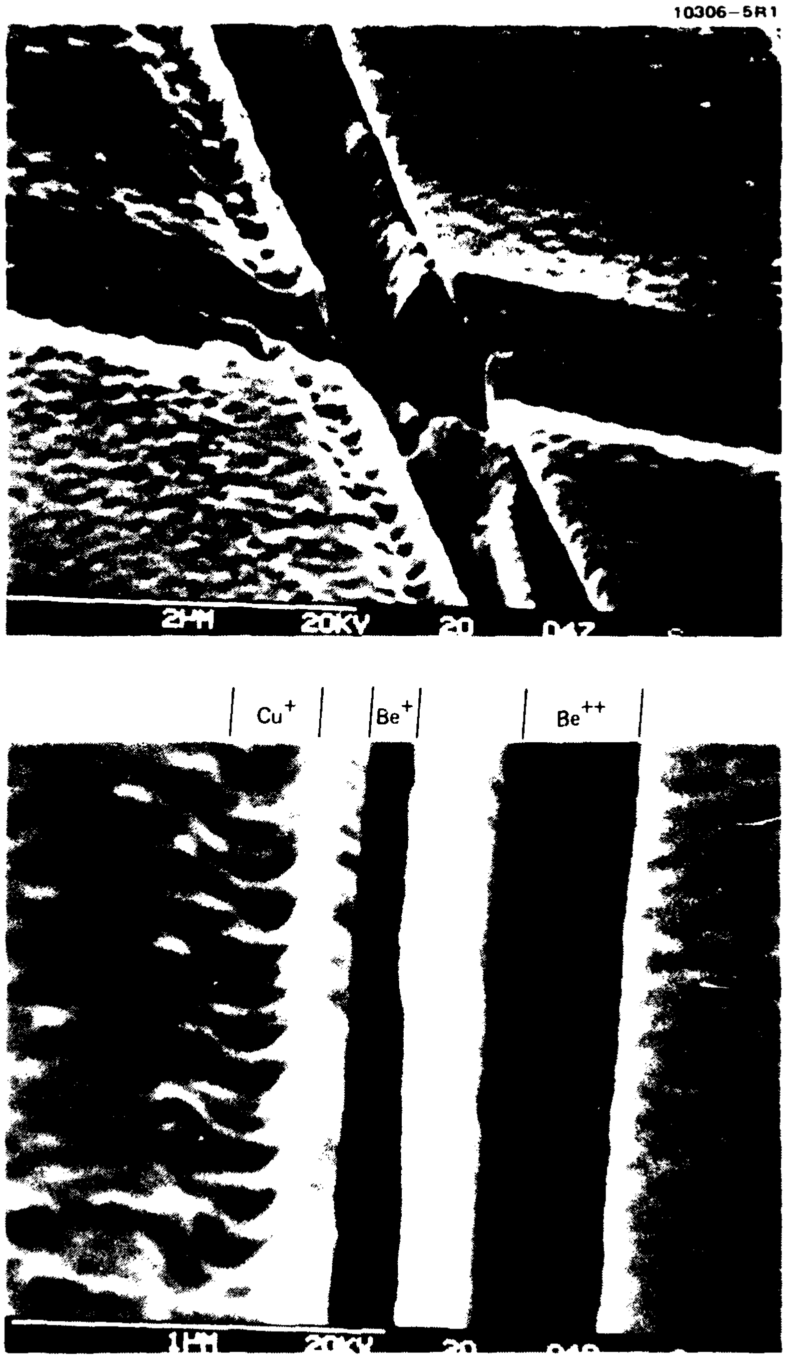

Figure 5. Mass separation of the Cu-Be beam due to earth's magnetic field.

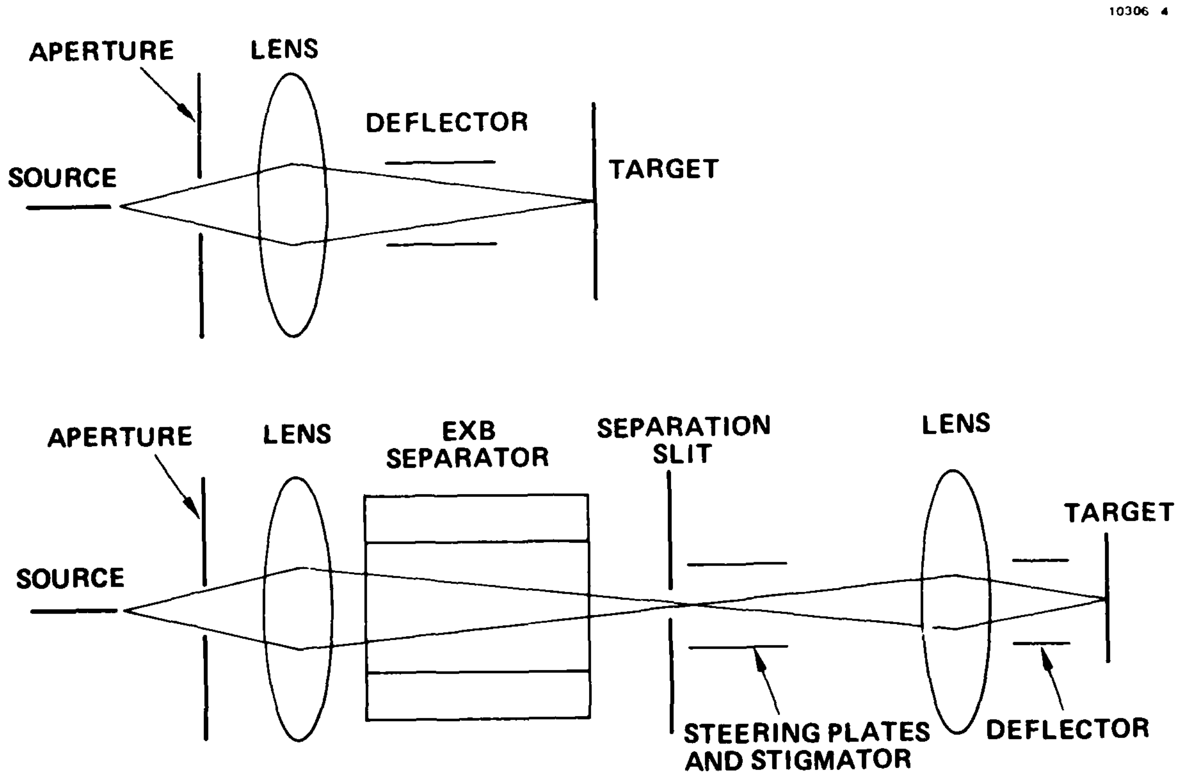

Figure 6. Comparison of required column components with and without mass separation.

system. For example, a very weak separator should be used with only enough dispersion to separate the isotopes of silicon. Thus, the beam crossover and separation slit must coincide. Calculations for such a system indicate that the astigmatism can, in fact, be held to an acceptable level.

Plans are currently underway to evaluate the effects of mass separation on ion beam focusing. These experiments will not only provide information concerning resist exposure, but will also provide the details necessary for an optimum column design.

IV. CONCLUSIONS

Although beryllium ions have significantly longer range at a given column potential than do silicon ions, the latter should probably be used to avoid any substrate contamination problems. Both the Cu-Si and Au-Si alloys can be used as ion source material.

Using an unseparated beam for both Be and Si alloys leads to a repolymerization of a positive resist at a dose slightly below maximum range. In addition to causing the repolymerization, the copper or gold ions could present a possible contamination problem.

Because the resist appears less sensitive to a high-current-density ion beam, resist for focused-ion-beam applications cannot be accurately characterized in a conventional, low-current-density apparatus (e.g., implant machine).

Although more complex, a focusing column employing mass separation appears to be the preferred technique for a direct-write ion-lithography system.

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